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# Evaluation of Performance and Greenhouse Gas Emissions for Plants Achieving Low Phosphorus Effluents

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# EVALUATION OF PERFORMANCE AND GREENHOUSE GAS EMISSIONS FOR PLANTS ACHIEVING LOW PHOSPHORUS EFFLUENTS


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WERF

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# ABSTRACT AND BENEFITS


**Abstract:**

This project included evaluation of operational practices and performance results for wastewater treatment plants designed to meet very low effluent total phosphorus (TP) concentrations. As stringent phosphorus limits of 0.1 mg/L and lower are becoming more common, there is a need to better understand factors impacting the sustainability of operating to meet these limits. This effort focuses on maximizing what can be learned from existing facilities to help utilities operate more sustainably while achieving the necessary level of performance.

Phosphorus removal practices were evaluated using performance data for 11 water resource recovery facilities (WRRFs). Assessments were made of overall performance, chemical consumption, influent characteristics, tertiary treatment performance, and resource recovery. Greenhouse gas emissions were estimated for the phosphorus removal component of each WRRF. In addition, several research elements were examined at full scale to help establish the effectiveness and the practical differences in performance. These items include impacts of chemical dosing location and waste chemical solids on phosphorus removal operation; impacts of primary sludge, return activated sludge (RAS) and mixed liquor suspended solids (MLSS) fermentation on enhanced biological phosphorus removal (EBPR); and impacts of EBPR on anaerobically digested biosolids dewaterability.


**Benefits:**

- ♦ Advances the database of technology performance statistics for WRRFs operating to meet stringent phosphorus limits and develops metrics to allow comparison between operating practices and results achieved.
- ♦ Provides a better understanding of differences between technologies by applying greenhouse gas (GHG) calculation methodologies to phosphorus removal at existing WRRFs operating to meet stringent limits.
- ♦ Identifies design and operating practices that impact phosphorus removal performance and consumption of resources.


**Keywords:** Phosphorus removal, limit of technology, sustainability, greenhouse gas emissions, case studies.

# TABLE OF CONTENTS

# LIST OF TABLES

# LIST OF FIGURES

# LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AWTP | Advanced Wastewater Treatment Plant |
| A2O | Anaerobic anoxic oxic |
| AO | Anaerobic oxic |
| BAF | Biologically active filter |
| Bio-P | Enhanced biological phosphorus removal |
| BNR | Biological nutrient removal |
| BOD | Biochemical oxygen demand |
| CaRRB | Centrate and RAS Reaeration Basins |
| cBOD | carbonaceous biochemical oxygen demand |
| CEPT | Chemically enhanced primary treatment |
| CH4 | Methane |
| COD | Chemical oxygen demand (mg $O_2$/L) |
| $CO_2$ | Carbon dioxide |
| $CO_2$ eq | Carbon dioxide equivalents |
| CWS | Clean Water Services |
| d | day |
| dtpd | dry tons per day |
| DO | Dissolved oxygen |
| EBPR | Enhanced biological phosphorus removal |
| EPS | Extracellular polymeric substances |
| FE | Final effluent |
| $Ft^3$ | Cubic feet |
| GHG | Greenhouse gas |
| GWh | Gigawatt hour |
| h | Hour |
| INF | Influent |
| IPCC | Intergovernmental Panel on Climate Change |
| Kg | kilogram |
| Kwh | Kilowatt hour |
| Lb | pound (mass) |
| LOT | Limits of technologies |
| $m^3$ | Cubic meters |
| MAP | Magnesium ammonium phosphate (struvite) |
| Mgd | Million gallons per day |
| Mg/L | milligrams per liter |
| MLE | Modified Ludzak-Ettinger |
| MLSS | Mixed liquor suspended solids |
| min | Minute |
| m-UCT | modified University of Cape Town |

| | |
|---|---|
| MWh | Megawatt hour |
| N | Nitrogen |
| $NH_3$-N | Total ammonia and ammonium as nitrogen |
| $NH_4$-N | Ammonium as nitrogen |
| $NO_2$-N | Nitrite as nitrogen |
| $NO_3$-N | Nitrate as nitrogen |
| NOx-N | Nitrite + Nitrate as nitrogen |
| $N_2O$ | Nitrous oxide |
| OP | Ortho phosphorus |
| ORP | Oxidation reduction potential |
| P | Phosphorus (mg/L) |
| PAO | Polyphosphate-accumulating organism |
| PE | Primary effluent |
| RAS | Return activated sludge |
| SCT | Solids contact tank |
| SE | Secondary effluent |
| sRP | soluble reactive phosphorus |
| SRT | Solids retention time |
| STP | Sewage treatment plant |
| TN | Total nitrogen |
| TP | Total phosphorus |
| TPS | Technology performance statistics |
| TSP | Total soluble phosphorus |
| TSS | Total suspended solids |
| UFAT | Unified fermentation and thickening process |
| U.S. EPA | United States Environmental Protection Agency |
| VFA | Volatile fatty acids |
| VIP | Virginia Initiative Plant (process) |
| WAS | Waste activated sludge |
| WEF | Water Environment Federation |
| WERF | Water Environment Research Foundation |
| WRF | Water Reclamation Facility |
| WRRF | Water Resource Recovery Facility |
| WWTF | Wastewater Treatment Facility |
| WWTP | Wastewater Treatment Plant |

# EXECUTIVE SUMMARY

## ES.1 Introduction

This research evaluated operational practices and performance results for wastewater treatment plants designed to meet very low effluent total phosphorus (TP) concentrations. Phosphorus removal practices were evaluated using performance data from 11 WRRFs. Assessments were made of overall chemical consumption, energy, carbon footprint, and resource use/recovery. In addition, several research elements were examined at full scale to help establish the effectiveness and the practical differences in performance. These items include impacts of chemical dosing location and waste chemical solids on phosphorus removal operation; impacts of primary sludge, return activated sludge (RAS) and mixed liquor suspended solids (MLSS) fermentation on enhanced biological phosphorus removal (EBPR); and impacts of EBPR on anaerobically digested biosolids dewaterability.

## ES.2 Methodology

Operating practices and phosphorus removal performance at 11 WRRFs were evaluated. The facilities included in this study were selected to cover a range of process flowsheets including several variations on EBPR and chemical phosphorus removal. The facilities also have differing solids handling practices which can impact operation for phosphorus removal.

There have been earlier reports evaluating WRRFs that achieve low effluent phosphorus levels. These reports set the baseline for this study by identifying technologies used and performance achieved (U.S. EPA, 2007) as well as the reliability for achieving the required effluent quality (Bott and Parker, 2011). Several of the treatment plants included in this study participated in this earlier work. However, the objectives for this project included carrying the evaluation further by assessing additional operational parameters and estimating the greenhouse gas (GHG) emissions associated with phosphorus removal. Parameters evaluated include phosphorus removal process performance, influent wastewater characteristics, effluent phosphorus limits, phosphorus removal operational philosophy, process monitoring strategies, and chemical dosing rates. In addition, solids management practices were examined for their impact on phosphorus removal and effects of phosphorus removal on solids handling. The results from each facility were compared to identify trends and operational practices for achieving phosphorus removal to low levels.

An estimate of GHG emissions was developed for each of the participating facilities. Process elements associated with phosphorus removal were identified by the project team and verified with each utility. These included mixing and pumping energy associated with operation of EBPR and tertiary treatment facilities as well as certain elements of solids handling processes that are impacted by phosphorus removal. Energy and chemical consumption associated with operation of these processes were determined from the operating data and were used as inputs for the GHG analysis. The facilities were then grouped by type of process, size, permit limit, and phosphorus concentration achieved to evaluate trends.

Finally, several issues affecting phosphorus removal performance were further examined using full scale data provided by the participating utilities. These issues include impacts of chemical dosing location and waste chemical solids on phosphorus removal operation; impacts of primary sludge, RAS and MLSS fermentation on EBPR and impacts of EBPR on solids dewaterability.

## ES.3 Conclusions

There were several key findings as follows:

- Maximum day concentration limits heavily impact operational practices and chemical consumption. Of the facilities evaluated, the four WRRFs with the lowest limits also had daily maximum phosphorus limits. One of these facilities had a very stringent maximum day limit of 0.1 mg/L and despite well-optimized EBPR and tertiary processes, chemical consumption was comparable to that of several plants operating with chemical addition only.
- In most cases, the WRRFs with the most stringent limits had lower variability ratios (ratio of TPS-91.7/TPS-50 or TPS-99.7/TPS-50). WRRFs operating EBPR without filters or chemical addition had higher variability ratios. A similar result was observed for plants with median limits.
- While influent BOD/TP ratio may provide an indication of the viability of EBPR, all three of the WRRFs that had BOD/TP ratios of 40 or higher needed to operate primary sludge or mixed liquor solids fermentation to provide the necessary volatile fatty acids. Of these, two were in cold climate and one was located in a warm climate. Regardless of the BOD/TP ratio, VFA must be available for optimal performance. Chemical consumption was highest for plants that are operated with tertiary phosphorus removal and have stringent limits of 0.05 mg/L TP or lower regardless of whether the main phosphorus removal process was EBPR or chemical addition.
- Optimization of EBPR performance coupled with attention to the tertiary phosphorus removal process allows chemical dosages to be reduced significantly. This was observed at Pinery WWTP, Kurt R. Segler WRF, and Iowa Hill WRF.
- Phosphorus recovery can enhance the reliability of EBPR by reducing the high phosphorus load in dewatering return streams.
- Although several of the WRRFs evaluated were equipped with online phosphorus analyzers and other process instrumentation, these analyzers were typically used for monitoring rather than control. Several of the facilities had flow paced chemical control or dosage rate control. However, all adjustments to chemical dosing adjustments were made manually. There may be an opportunity for optimization of chemical dosages by automating dosing control.
- As expected, the results from the GHG evaluation showed that the carbon footprint for phosphorus removal is heavily influenced by the permit limit. This can be tied to the need to add a higher dose of chemicals as well as operation of a tertiary treatment process to reach lower limits.
- Plant size did not seem to influence the GHG emissions for phosphorus removal amongst the plants studied. Permit limits had a much stronger relationship with GHG emissions.
- The carbon footprint for EBPR mixing, tertiary treatment, metal salt addition, and alkalinity addition for each WRRF comprised a significant portion of the total GHG emissions for these items varied significantly between plants. This suggests that there is significant opportunity to optimize these parameters. This is discussed further in Chapter 5.0.

- Although it was expected that chemical addition would comprise a high percentage of the P removal carbon footprint, it was noted that tertiary treatment energy consumption generated a similar level of GHG emissions.
- The impact of EBPR on solids dewatering represents an unknown from the perspective of overall sustainability. This is a critical issue in terms of needed improvements to the understanding of the mechanism and possible solutions.
- Waste chemical solids from tertiary phosphorus removal processes clearly are still active and can provide additional phosphorus removal if blended with the activated sludge process upstream.
- Alternative EBPR processes can be effective if adequate VFA are available.

## ES.4 Discussion

Although EBPR can be very effective in reducing phosphorus to low levels, it is clear that to meet the most stringent limits, chemical polishing is needed. As demonstrated by the plants participating in this study, there are a number of opportunities for optimization of chemical dosing, including practices such as returning waste chemical solids from tertiary treatment to the activated sludge process for additional phosphorus removal. Attention to the chemical injection design has also been shown to be critical for ensuring full effectiveness of the dose in reaching low concentrations.

EBPR offers an opportunity at some WRRFs to minimize chemical dosing and reduce the carbon footprint, but only if it is designed to minimize energy inputs. It is essential that mixers and pumps not be oversized because an inefficient pump and mixer design will negate much of the savings in GHG emissions from reduced chemical consumption. Designers should focus on the lowest inputs needed, and be cognizant that the process basin layout and equipment sizing affect the energy requirements for the facility on a continuous basis throughout the life of the plant.

The impact of EBPR on digested solids dewaterability is an area that needs additional research. While there are several plants that have reported a decrease in digested sludge dewaterability and an increase in polymer dosing, the mechanisms for this apparent impact are not fully understood. Even with an increase in the carbon footprint to account for increased polymer dosing and less concentrated cake solids, the magnitude of this increase may be lower than the GHG emissions associated with high metal salt dosages. Methods for mitigating EBPR impacts on solids dewatering must be considered and evaluated on a site specific basis when selecting a phosphorus removal process.

No distinction was made between different methods of biosolids disposal and the impact of the fate of the phosphorus removed on the carbon footprint. GHG emissions were calculated for the increase in overall energy consumption or solids hauling associated with addition chemical solids produced as the result of phosphorus removal. Generally, decisions about biosolids processing depend heavily on the economics of disposal. This may vary considerably depending on the availability of land for application of Class A or Class B biosolids, or the availability of landfills for dewatered solids. These decisions are normally made independently from the type of liquid stream treatment required and it is difficult to account for difference in the fate of phosphorus when selecting a phosphorus removal process.

This study ultimately focused on how to minimize consumption of resources while maintaining reliable performance. However, the GHG emissions and overall sustainability of a process is significantly impacted by factors external to the plant operation or phosphorus removal process. Operators can use the available tools given to optimize performance and reduce consumption. Planners and managers must understand the balance between phosphorus removal process selection, solids handling and disposal practices, facility design, and community and financial impacts. Regulators must be cognizant of how effluent criteria may impact the design, operations, costs, and overall sustainability of WRRFs and be willing to consider alternatives that can meet water quality needs in a more sustainable manner.

## ES.5 Research Needs

The following research needs were identified during this study:

- The Pinery, Iowa Hill, and Kurt R. Segler plants all showed improved EBPR operation after they implemented fermentation of mixed liquor solids. Although several WRRFs have operated for mixed liquor fermentation, the mechanisms are not well understood and design criteria are not well defined. Confirmation of the mechanisms and design criteria would be helpful to practitioners looking to successfully apply this option.
- It has been documented that mixing intensity for chemical addition impacts dosing needs and the residual P concentration achieved. More information is needed to quantify these impacts at full-scale (design requirements, energy inputs, and actual impacts on dosing or performance results).
- There has been a recent focus on the impacts of EBPR on dewaterability of anaerobic digested solids. A negative impact has been observed at a number of WRRFs, including three that participated in this study. Additional work is needed to further confirm the mechanisms as well as develop and test means of mitigating this issue.

# CHAPTER 1.0

# PROJECT BACKGROUND

## 1.1 Introduction

This research evaluated operational practices and performance results for wastewater treatment plants designed to meet very low effluent total phosphorus (TP) concentrations. As stringent phosphorus limits of 0.1 mg/L and lower are becoming more common, there is a need to better understand factors impacting the sustainability of operating to these levels. This project evaluated operating practices and estimated GHG emissions associated with P removal at 11 WRRFs to help identify methods of operating more sustainably while achieving the necessary limits.

## 1.2 Project Background

WRRFs operating to achieve TP limits of approximately 0.1 mg/L and lower face special challenges. To meet very low effluent TP concentrations, tertiary chemical phosphorus removal tends to be the preferred option for reliable and consistent performance. As TP limits decrease, chemical dosages, energy, and manpower requirements can substantially increase. Each of these is costly and has its own environmental impact that is rarely considered when low effluent phosphorus limits are set.

EBPR can achieve effluent orthophosphorus (OP, or soluble reactive P) concentrations of less than 0.1 mg/L when optimized, allowing TP concentrations of lower than 0.3 mg/L to be achieved with filtration. However, to meet very low levels consistently, chemicals are required for precipitation of residual OP, coagulation of the remaining particulate and colloidal phosphorus, and to mitigate the risk of process failure. These low TP limits require nearly all particulate phosphorus be removed using highly efficient solids separation stages such as clarification followed by filtration, membrane filtration, or other tertiary process.

Some facilities have investigated the synergy of biological and chemical phosphorus removal (CPR), whereby chemicals are added as a polishing stage or in conjunction with EBPR. There are indications that even at plants that rely mostly on CPR, substantial saving in chemicals is possible through biological uptake, however the synergy between the two treatment methods is not clearly understood or defined.

To better understand and quantify chemical use, metal to phosphorus molar ratios observed at plants that are using chemicals need to be clearly defined. Some information in the literature is difficult to use due to ill-defined or inconsistent terms. Considering the synergies between EBPR and CPR processes, demonstrating the practical effects, and incorporating the research results into the design and operation of wastewater treatment processes is important to achieving sustainable phosphorus removal performance industry-wide.

The results of projects such as: Advanced Wastewater Treatment to Achieve Low Concentration of Phosphorus (EPA, 910-R-07-002); WERF Tertiary Phosphorus Removal Compendium (Neethling et al., 2008); WERF Project on Statistical Reliability in Achieving Limit of Technology Nutrient Removal (WEFTEC Workshop W101, 2008 – NUTR1R06h); WERF Reports 02-CTS-1, Sustainable Technology for Achieving Very Low Nitrogen and

Phosphorus Effluents (Pagilla et al., 2007); 01-CTS-3, Factors Influencing the Reliability of Enhanced Biological Phosphorus Removal (Neethling et al., 2005); NUTR1R06l, Phosphorus Fractionation and Removal in Wastewater Treatment – Implications for Minimizing Effluent Phosphorus (Gu et al., 2014); and NUTR1R06m, The Bioavailable Phosphorus (BAP) Fraction in Effluent from Advanced Secondary and Tertiary Treatment (Brett, 2015) comprise the current body of knowledge with respect to operation to achieve low effluent phosphorus concentrations. Recently, a great deal of research has been conducted to improve understanding of the mechanisms of CPR (Yang et al., 2006; Smith et al., 2007; Newcombe et al., 2008; Szabo et al., 2008). Information available from these recent reports and other observations from full-scale operation suggest that while low levels of phosphorus in effluents can be achieved, knowledge gaps remain in the application of research results to best sustainable phosphorus removal practice and on the interaction between chemical and biological processes for reliable phosphorus removal to varying lower levels (such as 0.1, 0.05, and 0.01 mg/L). This gap in "knowledge application" has also resulted in an unclear understanding of the mechanisms behind proprietary process technologies vs. the capabilities of established non-proprietary processes.

A more complete understanding of both the positive and negative impacts of metal salt addition to EBPR processes and the practical implications for operation is needed. Optimal points to add chemicals to the biological process (e.g., the anaerobic zone, aerated zone, or just before the clarifiers) and the impact of floc shear on EBPR and CPR need to be established. A better understanding of the aging of the mixture of biological and chemical solids and the role of solids contact time and solids retention time (SRT) on net chemical consumption and achievable P limits is also needed. A better assessment is needed regarding the optimal use of chemical sludge within tertiary processes, chemical sludge returned to the biological process, the impact of chemically enhanced primary treatment (CEPT) on the fate of phosphorus in digesters and return streams, liquid solids separation, and the implications when reclaiming struvite from return streams. Finally, the type and impact of solids management practices (thickening, stabilization, and dewatering) on phosphorus removal performance and the impact of phosphorus removal operation on biosolids handling processes need to be considered.

The results of recent research efforts need to be applied to normal operating practice. Then the implications of the research can be understood and applied across the industry. Positive outcomes include:

- Reduced chemical consumption for phosphorus removal, which will reduce the removal costs and environmental impacts associated with the use of those chemicals.
- A better understanding of the cost to achieve phosphorus removal at low levels and improved understanding of the need for (and potential avoidance of need for) advanced tertiary treatment processes.
- More clearly defined metrics to facilitate comparisons and optimization.
- A better understanding of the practical cost of the design and operational safety factors that are associated with different averaging periods for permit limits (e.g., annual vs. monthly vs. weekly averages).
- Understanding of the impacts of chemical addition on EBPR performance, specifically the potential for negatively impacting the PAOs when phosphorus is precipitated.
- Increased potential for recovery of phosphorus as a resource and reduced potential for struvite problems in sludge handling.
- Understanding of the impact of various solids/liquid separation options on low-P systems.

## 1.3 Objectives

The overall objectives of this project are two-fold. First, sustainable phosphorus removal practices will be examined by developing performance and sustainability metrics and assessing different process options based on the overall chemical consumption, energy, carbon footprint and resource use/recovery. A nutrient removal sustainability baseline has been developed under the WERF project NUTR106n, *Striking the Balance between Wastewater Treatment Nutrient Removal and Sustainability* (Falk et al., 2010). This baseline information will be advanced by examining the actual carbon footprint for phosphorus removal operations for the participating utilities.

Second, findings from ongoing research to better understand the mechanisms of CPR and EBPR, and the synergies between the two, must be applied in practice. Several research elements will be examined at full scale to help establish the effectiveness and the practical differences in performance. These items include impacts of chemical dosing location and waste chemical solids on phosphorus removal operation; impacts of primary sludge, RAS and MLSS fermentation on EBPR; and impacts of EBPR on anaerobically digested biosolids dewaterability.

## 1.4 Approach

Operating practices and phosphorus removal performance at 11 WWRFs were evaluated. The facilities included in this study were selected to cover a range of process flowsheets including several variations on EBPR and chemical phosphorus removal. The facilities also have differing solids handling practices which can impact operation for phosphorus removal.

There have been earlier reports evaluating WRRFs that achieve low phosphorus levels. These reports set the baseline for this study by identifying technologies used and performance achieved (U.S. EPA, 2007) as well as the reliability for achieving the required effluent quality (Bott and Parker, 2011). Several of the treatment plants included in this study participated in this earlier work. However, the objectives for this project included carrying the evaluation further by assessing additional operational parameters and estimating the carbon footprint associated with phosphorus removal operation.

Plant effluent data included in this study consist of flow proportioned composite samples. Monitoring data provided for individual plant processes consist of discrete samples as well as composite samples (in most cases, composite samples within the plant consist of equal aliquots collected every 30 to 60 minutes, rather than the flow-proportioned composite samples typically used for reporting). Generally, all of the plants kept daily records of chemical consumption and most provided annual records for energy consumption and biosolids hauling. Similar to previous WERF projects, plant operating data was accepted without independent confirmation of analytical work as all of the facilities are subject to federal regulations for accurate reporting of data. However, the data sets were checked for database entry errors (such as negative values or missing decimal points) and to ensure that the data were reasonable (for example that OP values were lower than TP values analyzed for the same sample).

Parameters evaluated include phosphorus removal process performance, influent wastewater characteristics, effluent phosphorus limits, phosphorus removal operational philosophy, process monitoring strategies, and chemical dosing rates. In addition, solids management practices were examined for their impact on phosphorus removal and effects of phosphorus removal on solids handling. The results from each facility were compared to identify trends and operational practices for achieving phosphorus removal to low levels as detailed in Chapter 2.0 and Appendices A through K.

An estimate of GHG emissions associated with P removal was developed for each of the participating facilities. Process elements associated with phosphorus removal were identified by the project team and verified with each utility. These included mixing and pumping energy associated with operation of EBPR and tertiary treatment facilities as well as certain elements of solids handling processes that are impacted by phosphorus removal. Energy and chemical consumption associated with operation of these processes were determined from the operating data and were used as inputs for the GHG analysis. The facilities were then grouped by type of process, size, permit limit and phosphorus concentration achieved to evaluate trends. The results are presented in Chapter 3.0.

Finally, several issues affecting phosphorus removal performance were further examined using full scale data provided by the participating utilities (Chapter 4.0). As discussed earlier, these issues generally include impacts of chemical dosing location and waste chemical solids on phosphorus removal operation; impacts of primary sludge, RAS and MLSS fermentation on EBPR and impacts of EBPR on solids dewaterability. Specific issues examined included:

- Impact of waste chemical solids on phosphorus removal operation at the Snake River, Farmers Korner and Iowa Hill facilities.
- Chemical dosing interruptions at Blue Plains AWTP.
- Benefit of fermenter operation at Kalispell AWTP.
- Enhancement of EBPR at Iowa Hill WRF using mixed liquor fermentation.
- Pilot testing of a small-footprint EBPR process at the Robert W. Hite treatment facility.
- Dewaterability of anaerobically digested EBPR biosolids (Durham AWWTF, Rock Creek AWWTF, and Robert W. Hite Treatment Facility).

As mentioned earlier, data for these evaluations was requested and kindly shared by the participating utilities. Several of the studies were conducted concurrently with this project and the project team was able to participate in the planning discussions prior to and during testing. These included Kalispell AWWTF chemical addition, Iowa Hill WRF mixed liquor fermentation testing, and the small-footprint EBPR testing at the Robert W. Hite facility.

# CHAPTER 2.0

# EVALUATION OF OPERATIONAL PRACTICES AT PLANTS ACHIEVING LOW EFFLUENT PHOSPHORUS CONCENTRATIONS

## 2.1 Introduction

The first phase of this study consisted of evaluating 11 WRRFs that are operated for phosphorus removal. The facilities studied were selected to cover a range of processes including several variations on EBPR and chemical phosphorus removal. The facilities have differing solids handling practices which also can impact operation for phosphorus removal.

There have been earlier reports evaluating operation to low phosphorus levels. These reports set the baseline for this study by identifying technologies used and performance achieved (U.S. EPA, 2007) as well as the reliability for achieving the required effluent quality (WERF, 2011). Several of the treatment plants included in this study also participated in the earlier work.

This research carries the previous studies further by assessing additional operational parameters and estimating the carbon footprint associated with phosphorus removal. Parameters evaluated include phosphorus removal process reliability, influent wastewater characteristics, effluent phosphorus limits, phosphorus removal operational philosophy, process monitoring strategies, and chemical dosing rates. The results from each facility were then compared to identify trends and best operational practices for achieving phosphorus removal to low levels as detailed in this chapter. The information from the participating facilities was later used to estimate GHG emissions related to phosphorus removal as discussed in Chapter 3.0.

## 2.2 Participating Utilities

Eleven WRRFs were evaluated in this study. For each facility a minimum of three years of operating data were evaluated (with the exception of Kurt R. Segler WRF in Nevada where two years of data were available). A detailed report was developed for each plant including schematics, effluent permit requirements, influent wastewater characteristics, description of phosphorus removal strategy and operational practices, assessment of operating results, chemical consumption, biosolids management, and operations staffing. These reports are provided in Appendices A through K. A summary of the facilities evaluated is shown in Table 2-1.

Table 2-1. Phosphorus Removal Plants.

| Plant | Capacity | TP Limit | Phosphorus Removal Process | Biosolids Processes |
|---|---|---|---|---|
| Kalispell AWWTF, Montana<br>(Appendix A; Emrick, 2009) | 5.4 mgd | 1 mg/L monthly average | EBPR (first with m-UCT, later with Johannesburg), primary sludge fermenter for VFA supplementation, filters, no chemical. | Fermentation/gravity thickening of primary sludge, DAF thickening of WAS, anaerobic digestion of primary sludge, BFP dewatering of digested solids and TWAS. |
| Durham AWWTF, Oregon<br>(Appendix B) | 25 mgd | 0.11 mg/L monthly median (summer season) | Intermittent CEPT, EBPR using A2O process, primary sludge fermenter for VFA supplementation, chemical addition followed by tertiary clarifiers and effluent filters, struvite recovery. | Fermentation/gravity thickening of primary sludge, centrifuge thickening of WAS, WASSTRIP, anaerobic digestion, centrifuge dewatering, controlled centrate return. |
| Rock Creek AWWTF, Oregon<br>(Appendix C; Spani, 2008) | 39 mgd | 0.10 mg/L monthly median (summer season) | CEPT , EBPR using A2O process, chemical addition followed by tertiary clarifiers and filters, struvite recovery. | GBT thickening of combined primary sludge and WAS, anaerobic digestion, centrifuge dewatering. |
| Virginia Initiative Plant, Virginia<br>(Appendix D) | 40 mgd | 2 mg/L annual average concentration; 122,822 lb/yr mass limit (1 mg/L at 40 mgd) | EBPR using VIP process, no filters, no chemicals. | Gravity thickening of primary sludge, centrifuge thickening of WAS, centrifuge dewatering of thickened sludges, incineration. |
| Empire WWTP, Minnesota<br>(Appendix E) | 24 mgd | 1 mg/L as 12-month rolling average; 39,525 kg/yr | EBPR using A/O process, no filtration. | Gravity thickeners for primary sludge, GBT for WAS, anaerobic digestion, BFP dewatering. |
| Pinery WWTP, Colorado<br>(Appendix F; Clark and Neethling, 2009) | 2 mgd | 0.05 mg/L monthly average; 0.10 mg/L daily maximum | EBPR using 5-stage Bardenpho configuration, chemical addition, tertiary treatment using U.S. Filter Trident system. | WAS is directed to holding tank and dewatered using BFP. Dewatered solids are composted. |
| Iowa Hill WRF, Colorado<br>(Appendix G; Maher, 2008; Maher et al., 2011) | 1.5 mgd (no longer in operation) | 225 lb/yr or 0.05 mg/L average; 0.5 mg/L daily maximum | EBPR using A/O process, nitrification BAF, tertiary chemical addition and settling using Densadeg system, filtration. | WAS is returned to sewer and transferred to Farmers Korner plant. |
| Farmers Korner WWTF, Colorado<br>(Appendix H; Maher et al., 2011) | 5.1 mgd | 483 lb/yr or 0.031 mg/L average; 0.5 mg/L daily maximum | Tertiary phosphorus removal; one side with flocculation and tube settlers, the other with Densadeg; filters. | Aerobic digestion of WAS and dewatering |
| Snake River WWTP, Colorado<br>(Appendix I) | 2.6 mgd | 340 lb/yr, 0.043 mg/L, 0.5 mg/L daily maximum | Tertiary phosphorus removal with chemical addition, solids contact clarifiers, filtration. | Aerobic digestion and centrifuge dewatering. |

| Plant | Capacity | TP Limit | Phosphorus Removal Process | Biosolids Processes |
|---|---|---|---|---|
| Kurt R. Segler WRF, Nevada<br>(Appendix J) | 32 mgd | 41 lb/d (0.15 mg/L at 32 mgd capacity) | EBPR using Johannesburg configuration, tertiary chemical treatment, filtration. | Aerated holding tank, BFP dewatering. |
| Blue Plains AWTP, Washington, DC<br>(Appendix K; Bailey and Murthy, 2008) | 370 mgd | 0.18 mg/L annual average, 0.35 mg/L weekly average | Multi-point chemical addition at primary clarifiers and secondary treatment, filtration. | Gravity thickening of primary sludge, DAF thickening of WAS, centrifuge dewatering, lime stabilization. |

## 2.3 Phosphorus Removal Performance Statistics

The performance of each WRRF was evaluated for its reliability in achieving certain effluent phosphorus concentrations. The methodology developed by Bott and Parker (2011) was used to determine the phosphorus removal technology performance statistics (TPS). Several statistical measures of the data are reported. First, since a number of the facilities are regulated based on an annual average concentration basis (such as Blue Plains) or on an annual average mass loading allocation (such as Snake River, Iowa Hill, and Farmers Korner) the annual average concentration was reported. Similarly, 50$^{th}$ percentile or median concentrations are shown since some facilities (Rock Creek and Durham) have permits based on monthly median limits. Finally, TPS values for the 91.7 and 99.7 percentile values are shown to provide an indication of the levels that were achieved on a maximum month or peak day statistical basis.

The TPS values provide a measure of the achievable performance of a treatment plant in the past. However, it does not directly provide a measure of the reliability to meet a permit limit. The TPS-91.7 or 91.7$^{th}$ percentile, which represents the statistical maximum month concentration, is exceeded once in 12 periods, or one month in a year. Statistically speaking, if that is the permit, the treatment plant will exceed this value once a year. The reliable concentration will be at a higher percentile. A 95$^{th}$ percentile, for example, implies exceedances of 5%, or three potential monthly exceedances in 60-month (five-year) period.

Within the individual plant summary reports included in the Appendices, log-normal distributions for the entire multi-year dataset for each plant are included, along with a table listing the statistical values for each calendar year examined. In Table 2-2, the TPS are reported for a period of three consecutive years. Variability ratios for TPS-91.7/TPS-50 and TPS-99.7/TPS-50 also are shown.

Table 2-2. Phosphorus Removal TPS.

| Plant | Average TP, mg/L | 50th Percentile TP, mg/L | 91.7 Percentile TP, mg/L | 99.7 Percentile TP, mg/L | TPS-91.7/TPS-50 [TPS-99.7/TPS-50] | Notes |
|---|---|---|---|---|---|---|
| Kalispell AWWTF | 0.13 | 0.11 | 0.2 | 0.72 | 1.82 [6.55] | 2006 through 2008. Effluent sampling conducted twice weekly. |
| Durham AWWTF | 0.107 | 0.072 | 0.22 | 0.92 | 3.06 [12.78] | 2010 through 2012 phosphorus removal seasons (May 1 through October 31). Daily effluent sampling. |
| Rock Creek AWWTF | 0.155 | 0.082 | 0.245 | 3.24 | 2.99 [39.51] | 2011 through 2013 phosphorus removal seasons (May 1 through October 31). Daily effluent sampling. |
| Virginia Initiative Plant | 0.49 | 0.31 | 1.20 | 3.24 | 3.87 [10.45] | 2009 through 2011. Effluent sampling conducted 5 days per week. |
| Empire WWTP | 0.43 | 0.28 | 0.69 | 5.69 | 2.46 [20.32] | 2009 through 2001. Effluent sampling conducted 5 days per week. |
| Pinery WWTP | 0.035 | 0.033 | 0.051 | 0.082 | 1.55 [2.48] | 2011 through 2013. Effluent sampling conducted twice weekly. |
| Iowa Hill WRF | 0.016 | 0.013 | 0.028 | 0.09 | 2.15 [6.9] | 2009 through 2011. Effluent sampling conducted twice weekly. |
| Farmers Korner WWTF | 0.012 | 0.012 | 0.024 | 0.031 | 2.0 [2.58] | 2009 through 2011. Effluent sampling conducted weekly. |
| Snake River WWTP | 0.020 | 0.015 | 0.039 | 0.178 | 2.6 [11.87] | 2008 through 2010. Daily effluent sampling. |
| Kurt R. Segler WRF | 0.13 | 0.12 | 0.21 | 0.49 | 1.75 [4.08] | 2011 through 2012. Daily effluent sampling. |
| Blue Plains AWTP | 0.07 | 0.06 | 0.13 | 0.38 | 2.17 [6.33] | 2011 through 2013. Daily effluent sampling. |

Of the 11 WRRFs evaluated, five achieved TP concentrations lower than 0.10 mg/L on average. The performance results are grouped as follows:

- The plants with daily limits also have the lowest monthly or annual average limits and achieved the lowest effluent phosphorus concentrations. This group includes Pinery, Iowa Hill, Farmers Korner, and Snake River. Of this grouping two (Farmers Korner and Snake River) use chemical phosphorus removal only while the other two (Pinery and Iowa Hill) use a combination of EBPR and chemical polishing. In comparing the daily maximum and annual average limits for each of these plants, it is noted that for Iowa Hill, Farmers Korner, and Snake River, the daily maximum is about 10 times higher than the allowable average. Pinery has a daily maximum limit of about twice the allowable average. In terms of the TPS achieved by these plants, the 99.7 percentile is approximately three to eight times higher than the average. This grouping of plants also generally had the lowest variability ratios of the plants studied (with the exception of Snake River WWTP).
- Of the remaining plants, Blue Plains achieved the best average performance with effluent TP concentrations of 0.07 mg/L. This is likely the result of the weekly maximum limit and the accompanying operating philosophy. The 98.1 percentile value (corresponds to one weekly exceedance per year) for Blue Plains is 0.18 mg/L.
- Kalispell, Durham, Rock Creek, and Kurt R. Segler achieved average concentrations in the range of 0.10 to 0.16 mg/L. Kalispell and Kurt R. Segler both have 50$^{th}$ percentile values that are slightly lower but close to the average values. Durham and Rock Creek achieve 50$^{th}$ percentile values that are significantly lower than the average values, which reflects operation for median limits.
- Empire and VIP have TP limits in the 1 to 2 mg/L range and operate without chemical addition or filters. Both plants are subject to larger variations in performance as the result of having fewer ‘barriers” or treatment processes for phosphorus removal.
- Although Kalispell’s limit is 1 mg/L monthly average, optimization of EBPR, primary sludge fermentation, and filtration help reduce variations making this one of the most reliable phosphorus removal facilities even without the use of chemicals.

## 2.4 Chemical Dosing

A wide range of chemical dosage requirements has been reported for WRRFs achieving low TP limits. Generally, as limits decrease, WRRFs may find that molar ratios of 5 metal/P and higher are needed, particularly in the tertiary treatment process. However, these ratios can be misleading when examining total plant performance and have not always been reported in the same way in the literature.

Eight of the plants evaluated routinely use chemical addition as part of the phosphorus removal process. For each of these plants, molar metal salt to phosphorus ratios based on total phosphorus removed across the plant, were calculated. Many of the plants operate for some degree of tertiary chemical polishing and the molar metal to phosphorus dosing ratios for phosphorus removed through tertiary treatment are reported. For those plants that practice multi-point chemical addition, dosing ratios for individual processes are also reported if the supporting data were available. The results are summarized in Table 2-3.

Table 2-3. Chemical Dosing Ratios.

| Plant | Average Influent TP, mg/L | Average Effluent TP, mg/L | Total Plant Metal/P Ratio, mol/mol | Primary Treatment Metal/P Ratio, mol/mol | Secondary Treatment Metal/P Ratio, mol/mol | Tertiary Treatment Metal/P Ratio, mol/mol | Notes |
|---|---|---|---|---|---|---|---|
| Kalispell AWWTF | 4.7 | 0.13 | 0 | 0 | 0 | 0 | No chemical addition. |
| Durham AWWTF | 7.8 | 0.107 | 0.52 | 0.18 | 0.07 | 7.51 | 2010 through 2012. Alum. Tertiary waste chemical solids thickened with WAS. |
| Rock Creek AWWTF | 6.7 | 0.155 | 1.48 | 2.13 | 0 | 9.68 | 2011 through 2013. Alum. Tertiary waste chemical solids thickened with WAS. |
| Virginia Initiative Plant | 4.5 | 0.49 | 0 | 0 | 0 | 0 | EBPR only, no chemicals. |
| Empire WWTP | 8.2 | 0.43 | 0 | 0 | 0 | 0 | EBPR only. Minor ferric chloride dose to primary clarifiers for odor control. |
| Pinery WWTP | 7.8 | 0.035 | 1.75 | 0 | 0 | 54.5 | 2011 through 2013. Alum. Tert waste chem sludge to dewatering. |
| Iowa Hill WRF | 5.9 | 0.016 | 1.76 | 0 | 0 | 10.6 | 2009 through 2011. Alum. Tertiary waste chemical solids to collection system. |
| Farmers Korner WWTF | 5.6 | 0.012 | 2.25 | 0 | 0 | 23.5 | 2009 through 2011. Alum. Tert waste chem sludge to aerobic digesters. |
| Snake River WWTP | 5.6 | 0.02 | 1.37 | 0 | 0 | 6.85 | 2008 through 2010. Alum. Tertiary waste chemical solids sent to secondary treatment. |
| Kurt R. Segler WRF | 5.5 | 0.13 | 0.41 | 0 | 0 | 7.4 | 2011 through 2012. Alum. Tert waste chem sludge to dewatering. |
| Blue Plains AWTP | 4.8 | 0.07 | 1.08 | 1.4 | 0.92 | 0 | 2011 through 2013. Ferric chloride. High rate secondary ttmt w/ high sludge yield removes significant TP in solids. |